

OCCUPANT PROTECTION IN REAR-END COLLISIONS PRECEDED BY AUTONOMOUS EMERGENCY BRAKING DEPLOYMENT

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ABSTRACT

The safety of vehicle occupants has evolved recently due to the market implementations of new sensing technologies that enable predicting and identifying hazardous road traffic situations and thus actively prevent or mitigate collisions. The obvious benefits of the active safety systems has also been recognized and acknowledged by the regulatory and consumer bodies responsible for transportation, and as a result, the new standards, regulations and public rewards are being introduced.

The active safety systems can prevent or mitigate collisions by controlling the motion of the vehicles through autonomous actuation of either: braking, steering or both simultaneously. The autonomous control of the vehicle inevitably affects the motion of the travelling occupants with respect to the vehicle interior. Depending on the severity of the maneuver, the occupant motion may lead to non-optimal postures for the in-crash phase if the collision is unavoidable. This consideration creates the direct need for developing the active systems together with passive systems with the ultimate objective to best protect the occupants. This paper presents a simulation methodology for developing new automotive safety systems in an integrated manner that ensures optimal exploitation of benefits of predictive sensing and occupant restraints. It also demonstrates the application of the above methods, to investigate and optimize the occupant whiplash protection in rear-end collisions occurring during the autonomous emergency braking of the collided vehicle.

The investigation was performed using simulation techniques (MADYMO software). The driver occupant is initially exposed to the low-g longitudinal acceleration resulting from emergency braking, during which the rear-end acceleration pulse is applied, representing the collision conditions (following the High Severity Sled Pulse of Euro NCAP Whiplash testing protocol). Two different models of anthropometric test devices are used and compared: BioRID-II facet Q model and Active Human Model (AHM) to predict occupant motion while braking and assess injury risk as a result of the rear-end collision.

The results obtained showed the severity of the out-of-position occupant posture created by the autonomous braking maneuver, and its effect on injury risk in the consecutive collision. It was observed that the occupant motion resulting from braking is more pronounced in case of AHM than BioRID-II. Increased occupant travel during pre-braking impairs significantly the effectiveness of occupant rear-end protection restraint systems, thus increasing the whiplash injury risk. Further study demonstrates conceptual, pre-crash deployed safety solutions that alleviate the negative effects of the out-of-position postures created by pre-braking.

The study shows the need for developing the new safety systems in an integrated manner. It was performed based on the numerical simulations and some of the model components were not fully validated. The simulation methods and techniques will play a significant role in the integrated safety systems development processes, allowing testing the conditions of high complexity in order to represent the real life scenarios and thus ensuring better occupant protection.

INTRODUCTION

The introduction of Advanced Driver Assistance Systems (ADA systems or ADAS) generates new opportunities to mitigate the damage caused by traffic accidents or, in many cases, prevents them from happening. ADA systems such as Autonomous Emergency Braking System (AEBS) or lane change assist (LCA) support the driver in hazardous traffic situations by controlling longitudinal (by braking) and lateral (by steer torque) motion of the vehicle in case of collision risk. These systems, though relatively new to the market, have proved their significance for vehicle safety and are recognized already by legislative authorities and consumer bodies. The European Commission has introduced legislation for AEB and Lane Departure Warning (LDW) systems in commercial vehicles [1], and consumer testing protocols are currently available for AEB systems in the standard Euro NCAP protocol dedicated for city and interurban traffic.

Previous studies have shown that autonomous systems, such as AEB or autonomous steering, can lead to a non-optimal occupant posture and position resulting in reduced performance of the occupant restraint systems in case of a collision [2]. At the same time, the increasing presence of surround sensors allows for an improved performance of the passive safety systems by using information from before the crash. This information can be used to trigger restraint systems during the pre-crash phase e.g. pre-pretensioning of safety belts to reduce the occupant misalignments during pre-crash lateral or longitudinal loadings.

Previous studies [2], [3] have shown that the on-board restraint systems can be optimized in an integrated manner for a specific load case, i.e. frontal or side. The wide range of ADA systems available in the new vehicles can provide information about the vehicle's surrounding and can therefore be used to estimate the interaction with other vehicles resulting from the activation of a single ADA system. This plays an important role not only on the level of controllers implementation, but also on the occupants' protection: given a certain flow of actions initiated by the ADA controllers, the injuries suffered in an imminent collision might depend on the occupant Out Of Position (OOP) resulting from the avoidance of a preceding potential collision. With the more and more extensive implementation of AEB systems the urban areas have become a potential scenario for the combination of AEB actuations followed by a rear-end collision.

A first attempt of correlating the performance of an AEB system with the performance of the vehicle's restraint system in protecting the occupants in a rear collision has been done and described within this paper. The performance of the AEB system and the vehicle's restraint potential in limiting the whiplash injuries are awarded separately in the Euro NCAP protocol, with the only requirement of a minimum whiplash score for the vehicle to be eligible for the AEB City award.

This study presents a new application of the integrated safety method described in [2] with the analysis of the out of position resulting from the actuation of an AEB system before a rear collision. In line with the methodology, the advantage of predictive sensing for the optimization of the on-board restraint systems is confirmed, along with the difference in the injuries estimation between the BioRID-II dummy model and the active human model. The analysis is performed on a simulation level and extended with the activation of a selection of on-board restraint systems prior to the rear collision with the main objective of showing the different risk of high whiplash injuries with and without the preceding actuation of the AEB system.

METHODOLOGY

Currently, no experimental methods or simulation tools exist for evaluating the effects of pre-crash dynamics on the occupant injury risk during the crash phase. In this paper, the use of two software packages that together provide the potential to cover all critical aspects of the design of an integrated safety system is shown. One of the software packages (PreScan) focuses on the sensing and active control systems of a vehicle, and the other package (MADYMO) predicts an occupant response and injury risk throughout the whole pre- and potential in-crash event.

The methodology used in this study has been previously presented [2] when applied for the investigation into the frontal collision load case with pre-crash autonomous braking and the side collision load case with pre-crash triggered restrained systems [3]. In the current study, the methodology was appropriately adjusted to best represent

the phenomena characteristic for the problem of out-of-position while emergency braking, followed by a rear-end impact load case (See Figure 1).

The real world traffic situation is represented in PreScan in which the vehicle model under investigation, equipped with predictive sensors, is exposed to the collision risk situation. A control system based on the predictive sensors provides detection and initial classification of collidable objects (here referred to as targets), with respect to which the Time To Collision (TTC) information is estimated. Once the crash detection system model classifies the collision risk, the occupant's injury analysis is initiated in MADYMO with the initial conditions imported from PreScan. Based on the estimated TTC information sent to MADYMO, on-board restraint systems (e.g. belt pre-tensioners) are triggered in case of an unavoidable collision with the target. MADYMO uses the above listed information to calculate the deployment of restraints and compute the resultant occupant's posture. The outputs from MADYMO analysis is used to quantify the significance of active restraint systems in the rear-end collision.

The presented approach assumes that the pre-crash control system for rear-end collision placed on the struck vehicle does not affect the vehicle motion itself. Therefore, the collision conditions remain unchanged with and without the system. The pre-crash control system affects only the motion of the occupants by deploying the on-board restraint system before the crash in order to mitigate the injuries.

In the current study the methodology has been further extended to investigate the effects of AEBS actuations (vehicle pitching and braking) prior to the predicted rear collision. The origin of the pre-crash vehicle motion is not investigated in this study, but simply adopted as input to the MADYMO simulation to quantify the significance of occupant's misalignments and thus the out of position posture in the rear-end collision. The AEBS-induced vehicle motion is prescribed in MADYMO and synchronized with the rear-end crash pulse. The AEBS controller principle, its application and effects on the vehicle motion have been studied and described in [2].

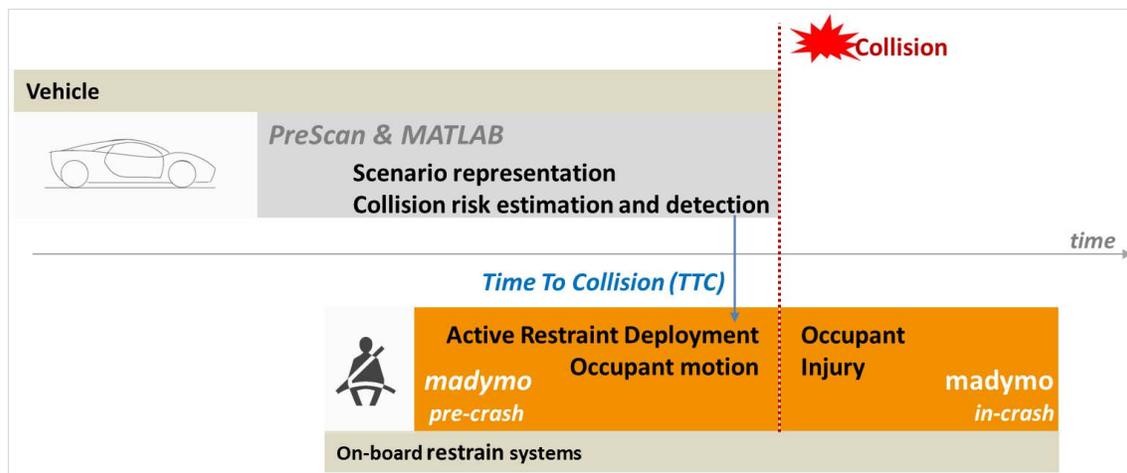


Figure1. Method.

Traffic scenario identification

Recent studies [4] confirm that in Germany rear-end collisions represent the third most common impact scenario after frontal and side impacts, and amount to 15% of all car accidents. Most of the car-to-car single rear-end collisions occur on urban roads [5] and 80% of rear-end collisions include accidents in longitudinal traffic conditions in which vehicles are stuck in a traffic jam or queuing at the traffic light [4].

Two traffic scenarios have been selected for this study and developed in the PreScan software, each representing a rear-end collision caused by a car (striking vehicle) failing to brake in the vicinity of a red traffic light and impacting the preceding car (struck vehicle) at the speed of 48 km/h. Two scenarios conditions for the struck vehicle are investigated:

1. The struck vehicle is stationary queuing at the traffic light
2. The struck vehicle drives at 56 km/h and comes to a full stop after the intervention of an AEB system to avoid a collision with the preceding stationary vehicle queuing at the traffic light.

The simulations of both traffic scenarios are shown in the Figure 2.

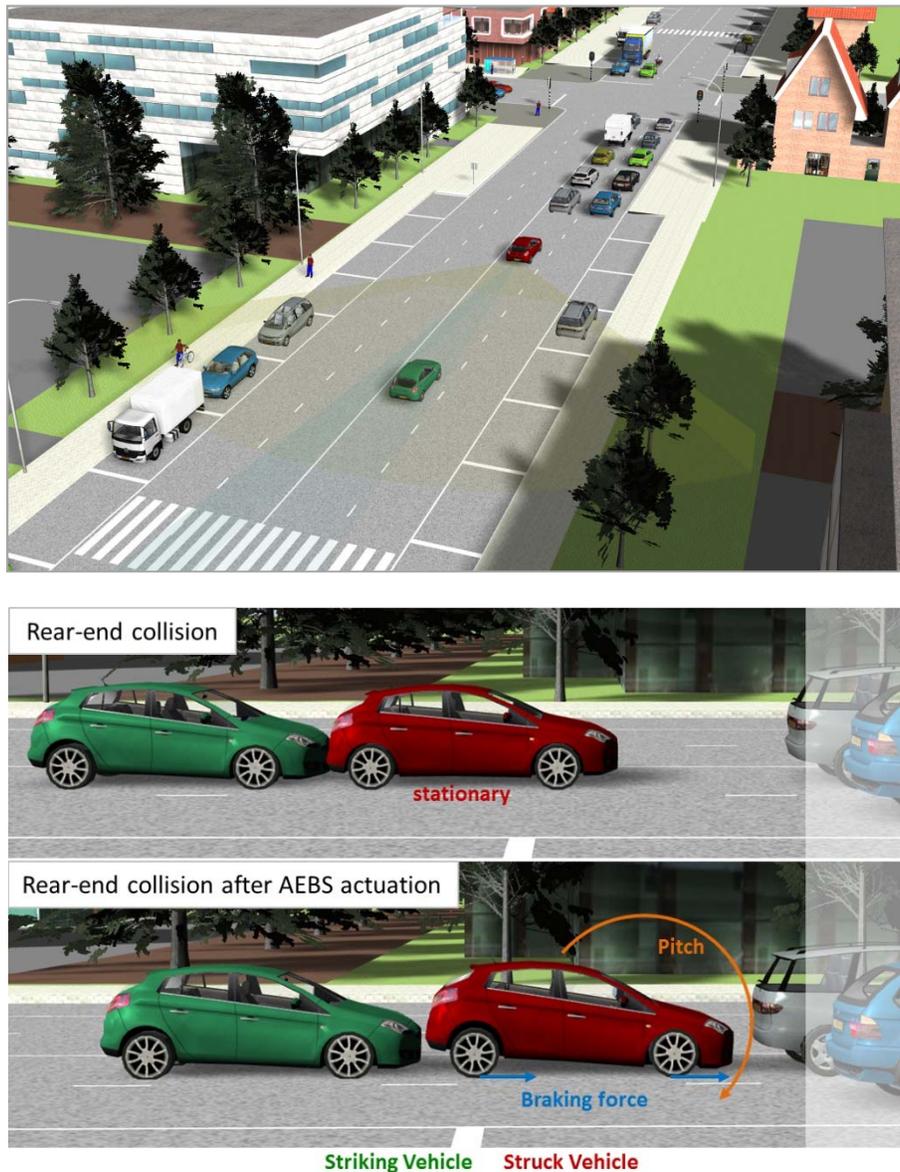


Figure2. Traffic Scenarios - Overview (top), details (bottom).

Maneuver dynamics of the struck vehicle model due to AEBS intervention

The deceleration and pitching profiles resulting from the activation of the AEB system have been computed by means of the PreScan embedded vehicle dynamics model [6]. A mid-class vehicle has been used for this study and it has been assumed that the maximum longitudinal braking force can be generated (dry asphalt, high friction). Supposing that the collision between the two vehicles is fully inelastic and both vehicles are of the same mass, the velocity change of 24.45 ± 1.2 km/h required by the Euro NCAP protocol (See section “Collision condition and investigated injuries”) implies a striking vehicle driving at the speed of 48 km/h. In line with the controller principles described in [2] due to the AEB intervention the struck vehicle undergoes a maximum longitudinal deceleration of 0.79 [g] and a maximum pitch angle of 1.4 [deg].

Collision condition and investigated injuries

In order to assess the occupant whiplash injury risk, the High Severity crash pulse of the Euro NCAP Whiplash protocol has been used [7]. The adopted crash pulse has been registered in a laboratory and complies with the Euro NCAP protocol requirements (not shown in this paper).

The same crash pulse has been used also in the traffic scenario involving the actuation of the AEB system. Although the initial conditions of the struck vehicle (pitching) do not fully comply with the sled test requirements (horizontally placed sled), it can be assumed that the small pitch angle does not compromise the validity of the crash pulse.

In line with the Euro NCAP dynamic test protocol, the injuries on the neck and thoracic spine are registered by means of a Bio-RID-II dummy, and quantified in terms of:

1. NIC peak
2. Maximum Nkm
3. Peak of Head rebound velocity
4. Maximum vertical and shear force on the Upper Neck
5. Peak of T1 acceleration
6. Time to first contact between the Head and the headrest

According to the protocol, all parameters except the rebound velocity are calculated up to the end of head to headrest contact.

The Euro NCAP parameters are calculated for both occupant models and it is therefore assumed that the limits (See Table 1) defined by the protocol are applicable also to outputs of the human model.

Table1.
Euro NCAP High Severity Pulse limits.

	Higher Performance Limit	Lower Performance Limit	Capping Limit
NIC [-]	13.00	23.00	25.50
Nkm [-]	0.22	0.47	0.78
Head Rebound Velocity [m/s]	4.10	5.50	6.00
Upper Neck Shear Force [kN]	30.00	210.00	364.00
Upper Neck Tension Force [kN]	470.00	770.00	1024.00
T1 acceleration [g]	12.50	15.90	17.80
Time to head- headrest contact [ms]	53.00	80.00	92.00

Rear collision detection principles

A controller algorithm and two radar sensors have been modelled to estimate the risk for the vehicle (host/struck vehicle) of being rear-struck by the vehicle coming from the back (striking vehicle). By means of a Long Range Radar (LRR, with one beam 150 [m] long and 8 [deg] wide) and a Short Range Radar (SRR, with one beam 30 [m] long and 80 [deg] wide) the area behind the host vehicle is scanned for targets. The sensors' readings are processed by the controller algorithm that computes the Time To Collision (TTC) based on which the on-board restraint systems can be triggered before the collision. The system (controller and sensors) acts in four steps to produce the TTC information with respect to the identified target vehicle (striking vehicle):

1. The LRR scans the surrounding of the host vehicle and identifies approaching objects. The TTC is calculated for each of them
2. Based on $TTC \leq 1.6$ [s] the target type identification process (object vs vehicle) is initiated
3. The SRR scans the surrounding of the host vehicle and identifies targets
4. If the same target is detected by both sensors and has been classified as a vehicle, the related TTC information is made available for the on board restraint systems to be triggered

The controller and the sensors have been implemented in PreScan, using Matlab/Simulink for the sensors' readings processing and for the computation of the TTC information.

Test sled and restraint systems models

The Euro NCAP Whiplash sled test has been reproduced in MADYMO with a seat including headrest, cushions and structure, a safety belt and a foot rest. The seat geometry is represented using facet surface technique and its compliance is expressed in terms of stress-strain characteristics representative of a generic middle-class vehicle seat. The model represents a generalized mid-size class passenger car and is validated for the three Euro NCAP whiplash sled pulses. The characteristics and properties of the seat are not shown in this paper. The belt is modelled with FE technique and represents the functionality of a belt system without locking mechanism and retraction functionality. To investigate the effectiveness of pre-crash deployed injury countermeasures the model is additionally equipped with the retractor pre-pretensioner (here referred to as pretensioner) and the active headrest prior to collision. The actuation of the active headrest aims at reducing the gap between the occupant's head and the seat and is implemented by prescribing the angular motion to a maximum angular displacement of 10 [deg]. The active headrest is actuated before the crash and can be triggered at the desired TTC based on the pre-crash vehicle sensors (i.e. radar sensor models). The actuation of the active retractor pretensioner to reduce the gap between the occupant and the backrest can be triggered with a pre-defined load at the desired TTC based on the pre-crash vehicle sensors (i.e. radar sensor models).

The design and optimization of the restraint systems actuation has been performed by means of simulations and has not been validated. The optimization enabled to define the triggering time (TTC) and the type of actuation (amount of angular headrest displacement and pretensioner loading force), and is not described in this study. The active restraint systems under investigation have been optimized for both load-cases and are listed in Table 2 together with the reference model (seat and seat-belt with no pre-crash activation).

Table2.
Restraint systems under investigation.

	Headrest forward rotation [deg]	Pretensioning load [kN]	Reference in the paper
Reference model	<i>n.a.</i>	<i>n.a.</i>	<i>Ref</i>
Active Headrest rotated forward	10	<i>n.a.</i>	<i>AH_10deg</i>
Retractor Pretensioner (1)	<i>n.a.</i>	0.15	<i>RPT_0.15kN</i>
Retractor Pretensioner (2)	<i>n.a.</i>	0.50	<i>RPT_0.50kN</i>
Combination of Active Headrest and Retractor Pretensioner (1)	10	0.15	<i>AH+RPT_0.15kN</i>
Combination of Active Headrest and Retractor Pretensioner (2)	10	0.50	<i>AH+RPT_0.50kN</i>

INVESTIGATION APPROACH

The paper describes the investigation into the effect of OOP induced by the (autonomous) actuation of an AEB system prior to a rear-end collision. The intervention of an AEB system alters the occupant's position with respect to the seat, thus affecting the restraining capabilities of the safety system. In the specific case, the AEB system actuation increases the relative distance between the occupant's head and the headrest, thus compromising the Euro NCAP Geometry assessment. As a consequence, the advantage of the restraint systems optimized according to (static) in-position requirements might be compromised.

In addition, the potential of triggering the on-board whiplash protection system prior to the rear-end collision is investigated. Based on the analysis of the whiplash injuries as required by Euro NCAP, the actuation and combination of active restraint systems is eventually analyzed.

Two occupant models are selected for the investigation, the MADYMO Active Human Model 50th percentile (here referred to as AHM) and the MADYMO BioRID-II Q facet dummy. The BioRID-II facet dummy is a well-

established ATD (Anthropometric Test Device), typically used in rear crash test protocols. It is extensively validated in numerous component, full scale and full system tests for in-plane rear loading [8].

The active human model has an improved biofidelity and includes muscle activity and posture maintenance activation: the neck, spine, elbows and hips can be controlled in order to try to maintain the initial position under the influence of external loading. The active human model is validated against volunteer and PMHS (Post Mortem Human Subject) test data for occupant pre-crash simulation of low-g frontal, as well as high- and low-g rear load-cases [9], [10], [11].

In the study, the neck, spine, elbows and hips of the human model are activated. The muscle activation settings used in the investigation represent an occupant that is aware about the upcoming collision and his muscles are initially braced (isometrically pre-tensed due to the psychological stress resulting from being in a dangerous situation). Occupant awareness/unawareness and bracing/relaxation are represented on the modeling level with two parameters: Muscle reaction time – time from 0 to 30ms represent an aware occupant Co-contraction – values above 0.5 represent braced occupant.

For both occupant models the same seat model is adopted, with the same initial orientation of both backrest and headrest. The BioRID-II has been placed into the seat making sure that the vertical and horizontal distances of the head with respect to the headrest are within the Euro NCAP corridors. The human model has been positioned assuring that the head-to-headrest position is as close as possible to the one of the BioRID-II (a maximum difference of 16 mm in the longitudinal direction). The seating procedure for both occupant models has been implemented by means of pre-simulations and is not described in this paper. The Figure 3 compares the position of both occupant models at the end of the AEBS intervention (before the rear-end collision) when placed on the same seat model. Due to the vehicle's deceleration and pitching, the occupant is displaced out of his initial position and the distances to the headrest and backrest increase. The Bio-RID-II shows a more significant out of position, with a longitudinal distance to the headrest five times higher than the initial value (41 [cm] versus 7.5 [cm]).



Figure3. Reference Model - Occupant models posture before the crash with and without previous AEB activation.

The sequence of events in case of a regular rear-end collision and a rear-end collision following the activation of an AEB system is shown in the Figure 4. In the regular rear-end collision all the active restraint systems are actuated based on the estimated risk of rear-end collision. With the AEBS intervention the retractor pretensioner is controlled by the AEB controller and triggered when the braking phase is initiated, while the headrest deployment is triggered based on the estimated rear-end collision.

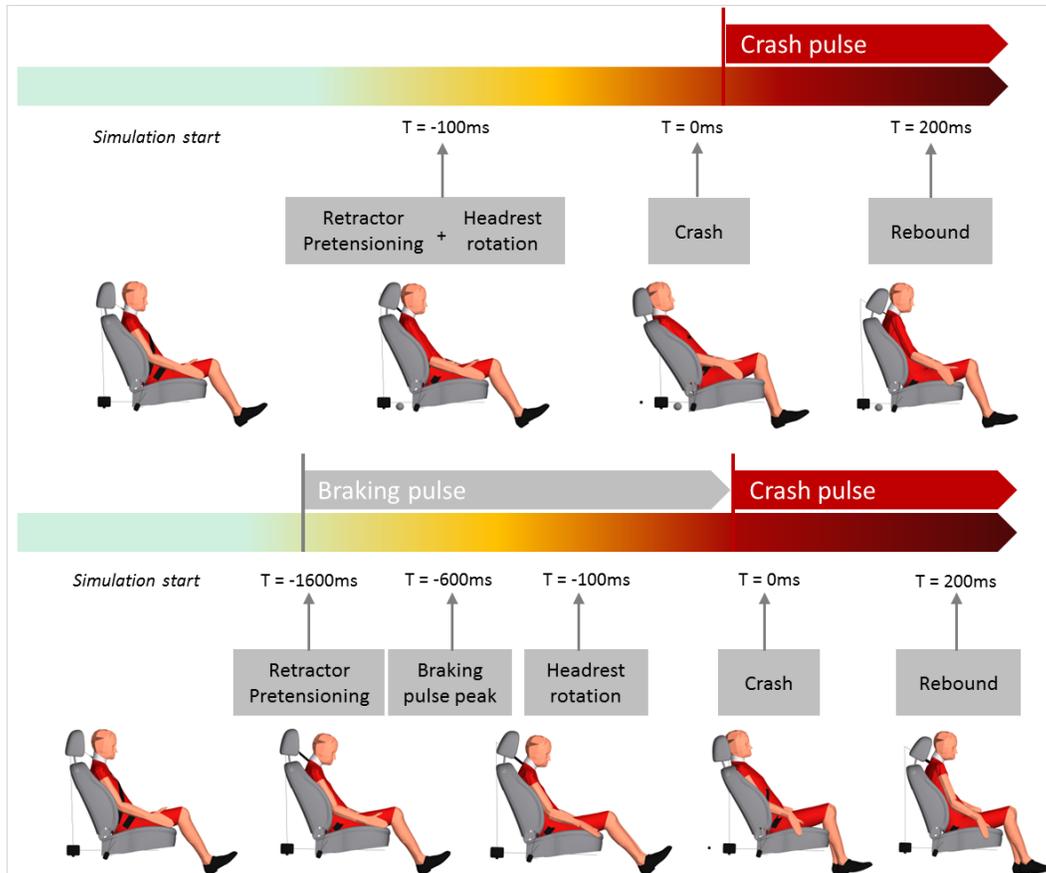


Figure 4. Sequence of events - Regular rear-end collision (top), rear-end collision after AEBS intervention (bottom).

In order to quantify the overall risk of high whiplash injuries, the Euro NCAP Lower Performance limits are assumed to be the maximum value (100%) with respect to the ideal situation of no injuries (0%): according to the Euro NCAP Whiplash test protocol, a criterion is awarded a “null score” if its value exceeds the Lower Performance Limit. The ratios (here referred to as Injury Ratios) between the in-simulation-observed injury values and the corresponding Lower Performance limits have been calculated and expressed in terms of percentages (100% corresponds to injury values equal to the Lower Performance limits). The injury ratios have been calculated for each of the seven injury criteria required by the Euro NCAP Whiplash test protocol and eventually averaged for each simulation (one simulation corresponds to one occupant model, one restraints configuration and one load case). It should be noted that the results evaluation has been carried out only with the Euro NCAP injury parameters and no analysis of the neck injury mechanisms has been performed.

WHIPLASH INJURY ANALYSIS RESULTS

The sensitivity of the reference restraint system to the load-case and to the occupant model is shown in the Figure 5. The activation of an AEBS always increases the risk of high whiplash injuries in a consequent rear-end collision, but the effect is differently quantified by the two occupant models: for the BioRID-II model the average injury ratio of 111% increases to 194%; a similar trend, though less pronounced, can be observed for the Active Human Model registering an average injury ratio increasing from 74% to 107%. The intervention of the AEBS amplifies also the difference between the occupant models: in a regular rear-end collision the BioRID-II produces whiplash injuries around 37% higher than the AHM, with the intervention of the AEBS the whiplash injuries are almost 90% higher for the BioRID-II.

The results with the reference models show a significant decrease in occupant protection resulting from the AEB-induced OOP, and thus create the need for the pre-crash intervention to correct the position of the occupant before entering the rear-end in-crash phase.

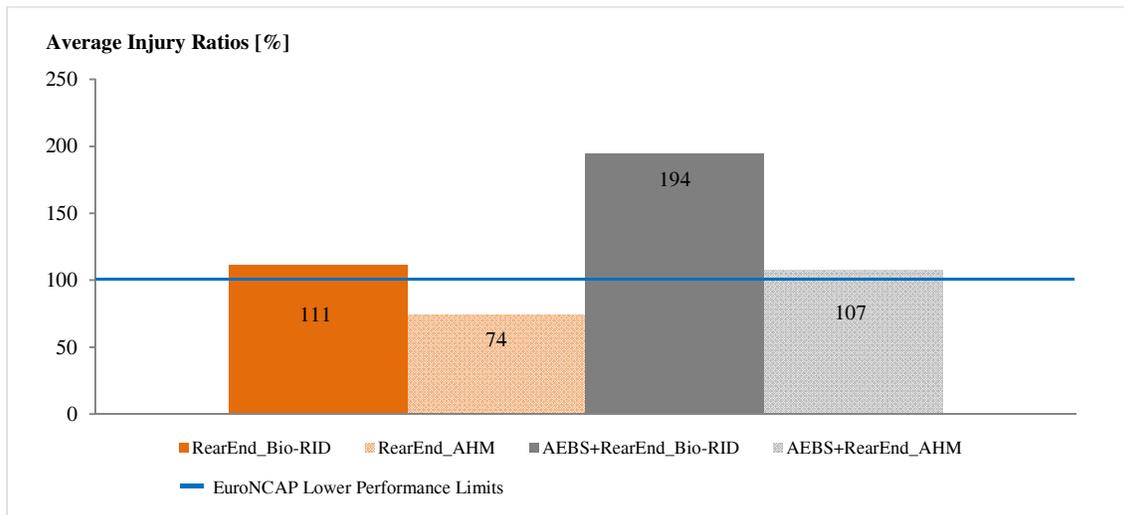


Figure5. Whiplash injuries in the reference models.

The effectiveness of different active restraint systems in reducing occupant injury values in rear-end load case with respect to the reference system is presented in the Figure 6. The two bar plots show the results for different ATD models: BioRID-II and AHM.

In case of the BioRID-II the 83% increase in the risk of high whiplash injuries caused by the AEBS (grey vs. orange bar) could be limited to a minimum of 74% by combining the active headrest and belt pretensioning. However, unlike the rear-end-only load case, triggering active systems in the pre-crash phase after an emergency braking always showed injury values still higher than the Euro NCAP Lower Performance limits. The potential of actuating the restraint systems before the rear-end collision proved always beneficial and similar trends in the injuries reduction after the AEBS actuation are observed. Depending on the applied system configuration the injuries are reduced by 18% - 55%.

In case of the AHM the 33% increase in the risk of high whiplash injuries caused by the AEBS (grey vs. orange bar) could be limited to a minimum of 5% by combining the active headrest and the belt pretensioning. Besides, triggering active systems in the pre-crash phase after an emergency braking always resulted in whiplash injuries equal to or lower than the Euro NCAP Lower Performance limits. The potential of actuating the restraint systems before the rear-end collision proved beneficial only after the AEBS deployment, with 8% - 25% lower injuries. In the rear-end-only load case the active restraint systems did not significantly affect the performance of the reference system: although no benefits have been found, a 5% increment has been observed.

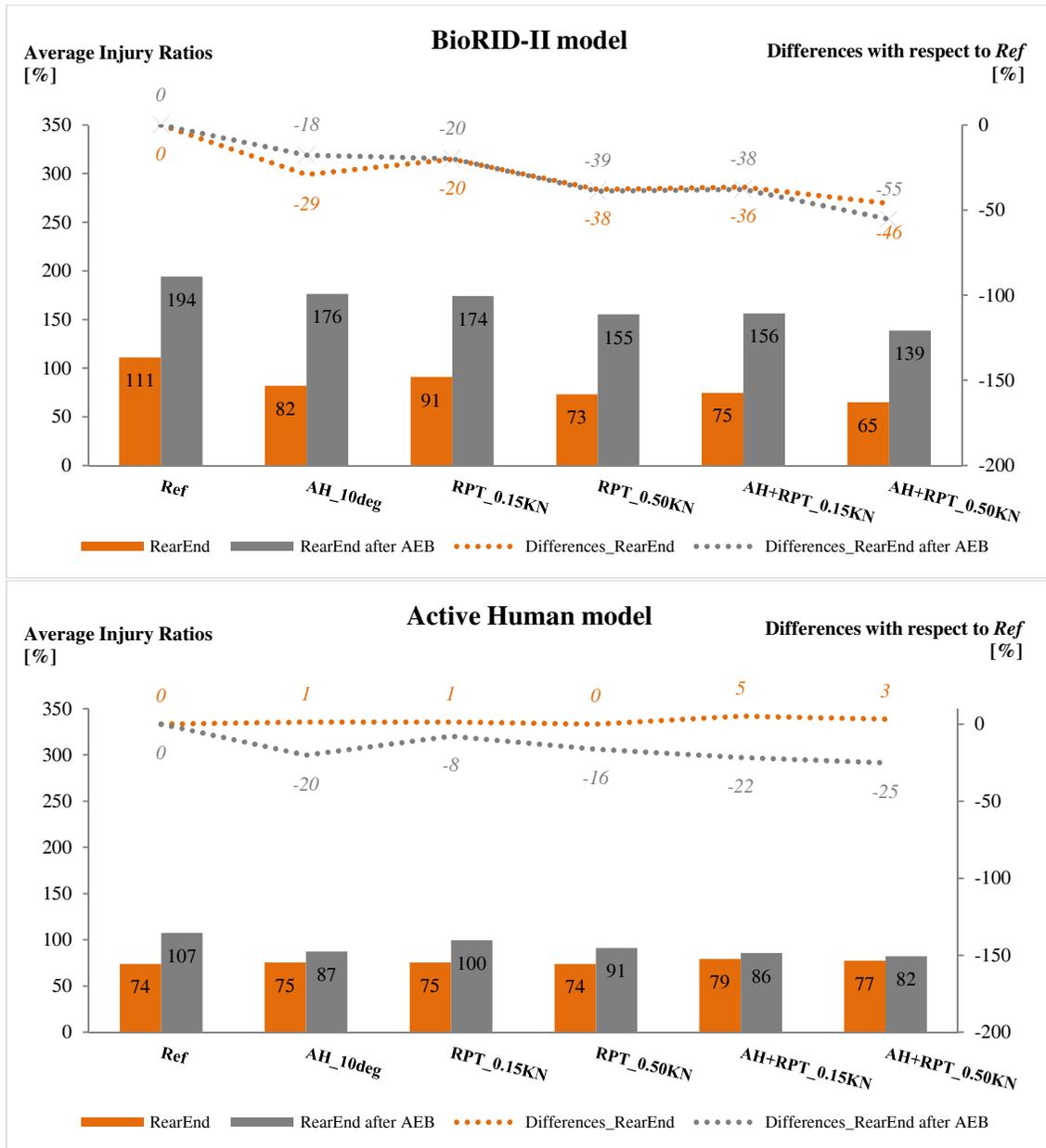


Figure 6. Average Injury Ratios with and without the intervention of the AEBS - BioRID-II (top) and Active Human Model (bottom).

The direct comparison between the injury results obtained with two ATD models (BioRID-II and AHM) throughout the active restraint systems under investigation is presented in the Figure 7.

The AEBS-induced OOP has differently affected the injury prediction of the occupant models. The difference in the injury values varies between 57% and 87% depending on the applied system configuration. In contrast with the simulations with the BioRID-II, triggering active systems in the pre-crash phase always showed average whiplash injuries lower than or equal to the Euro NCAP Lower Performance limits when simulating with the AHM: with the BioRID-II the risk of high whiplash injuries is in the range of 139% - 194%, while a much lower range of 82% - 107% has been observed with the human model.

The potential of actuating the restraint systems before the rear-end collision proved always beneficial and showed similar trends in the injuries reduction. However, with the AHM, the observed reduction of whiplash injuries is less than with the BioRID-II.

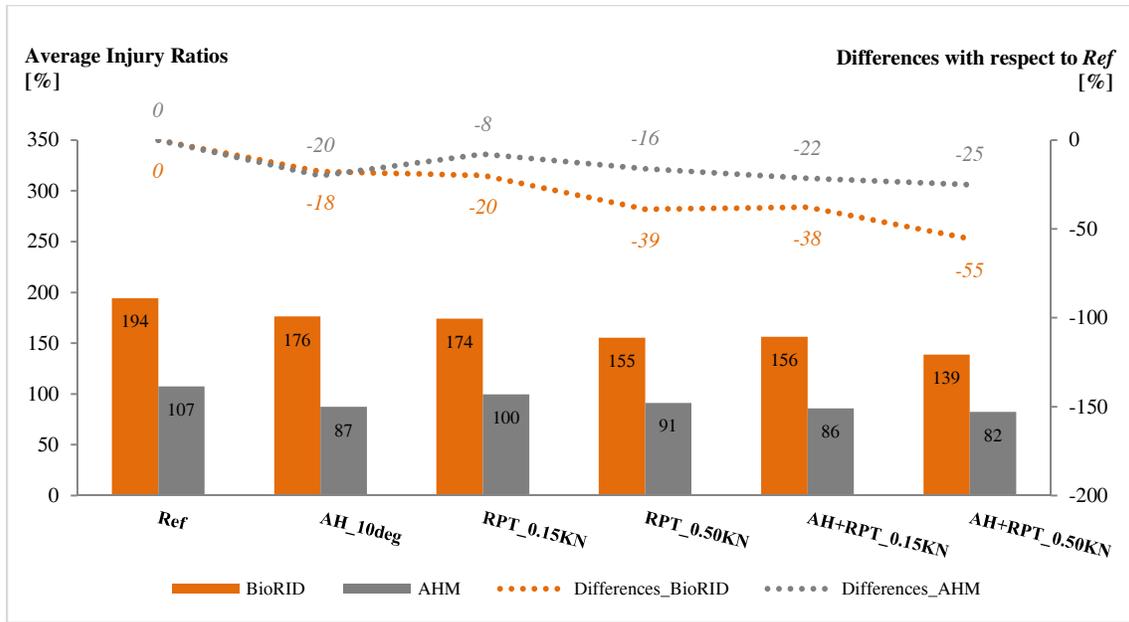


Figure7. Average Injury Ratios in the Rear-end collision after the AEBS intervention - Comparison between the occupant models.

Previous studies [11] prove that the initial seating posture and the head restraint position strongly influence the model response. In the study, the ratio between the head distance to the headrest and resulting injury values was found to be non-linear. In a regular rear-end collision reducing the initial gap between the head and the headrest reduces the risk of high whiplash injuries as long as the BioRID-II is used; with the human model no significant effect in the whiplash injuries has been observed when reducing the head to headrest gap (maximum increment of 5% in the injuries). In the Figure 8 the injury ratios observed with both occupant models are plotted with respect to the head-headrest distances (for clarity reasons, the results of the BioRID-II in the AEB scenarios are not entirely plotted). The reduction of the gap reduces the difference between the whiplash injuries of the BioRID-II and the AHM from 37% to 14%. In case of AEB-induced OOP, reducing the initial gap reduces the risk of high whiplash injuries. However, the gap reduction does not bring the risk of high whiplash injuries of the BioRID-II close to the ones of AHM, with differences in the range of 32% to 87%.

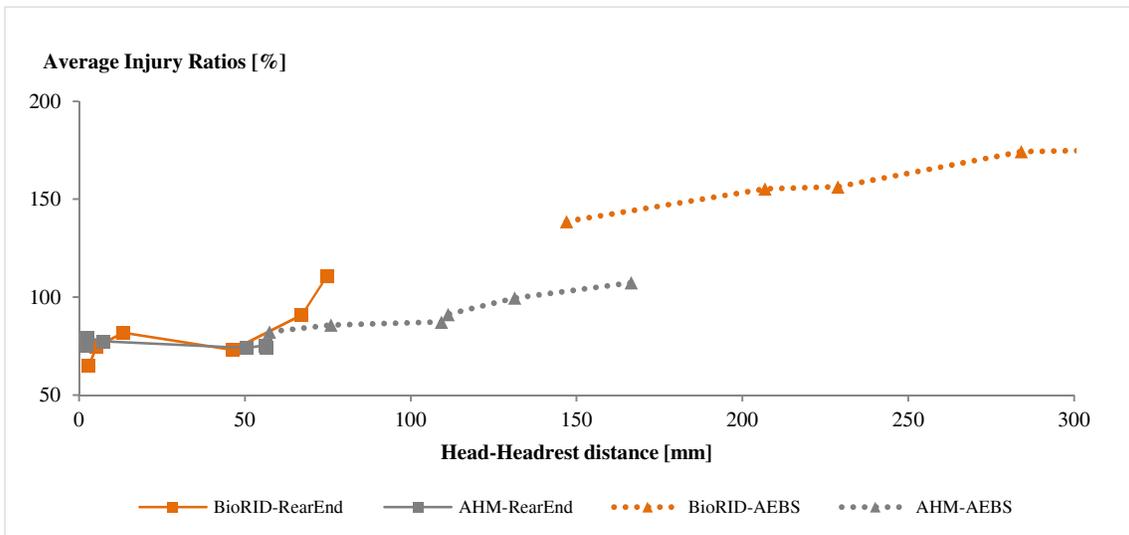


Figure8. Average Injury Ratios vs Head-Headrest distance

Results summary

With the intervention of an AEB system prior to a rear-end collision the risk of high whiplash injuries as a result of an altered seating position for the occupant (OOP) increases. The risks predicted by the BioRID-II increase by 83%, while in case of the AHM, the risks increase by 37%. For both occupant models the adoption of the active restraint systems cannot fully compensate the higher risk of high whiplash injuries caused by AEB-induced OOP, thus offering an overall protection level lower than in the regular rear-end collision (with no OOP).

The difference in the whiplash injury prediction between the occupant models changes radically between a regular rear-end collision and a rear-end collision after the actuation of an AEBS. Even though used with the same restraint systems and under the same loading conditions, in a rear-end collision the difference is in the range of 1% - 37%, while after the activation of the AEBS the difference can be as high as 57% - 89%.

The study shows that the intervention of active systems prior to a rear-end-only collision reduces the injuries to values lower than the Euro NCAP Lower Performance limits for both occupant models. The adoption of active restraint systems during the actuation of an emergency braking may result in an improvement with respect to the passive-only systems for both occupant models, but the whiplash injuries estimated by the BioRID-II remain above the Euro NCAP higher limits.

The BioRID-II model showed a consistent behavior in the prediction of the whiplash injury values with or without the intervention of the AEB system: in terms of risk reduction with respect to the reference model, the actuation of each active system has proved equally beneficial in both cases. On the other hand, with the AHM, only the AEBS-induced pre-collision loading shows the need for additional active restraint systems (which proved to be able to reduce the injury risk with a trend similar to the BioRID-II), while in a regular rear-end collision the level of protection of the reference system is neither improved, nor significantly worsened with the addition of active systems.

Reducing the head to headrest gap reduces the difference in the whiplash injuries estimation between the two occupant models for the regular rear-end collision. In case of AEB-induced OOP, the distances observed with the BioRID-II are significantly higher than the ones of the human model (150 – 400 [mm] range for the first, 55 – 180 [mm] range for the latter).

CONCLUSIONS

A methodology for the development of passive and active safety systems in an integrated manner has been drafted and motivated in this paper. Due to the increased implementation of autonomous functions in the new vehicles (e.g. AEBS), there is also an increased need for investigating and testing the consequences of operation of such systems on occupant safety. The protocols assessing the whiplash injury risk in a rear-struck vehicle adopt a BioRID-II dummy in the dynamic tests for which a crash pulse is applied to an initially stationary sled, thus assuming no prior AEBS actions. With the analysis of an altered initial state of the vehicle (due to AEBS) the established protocols and the occupant model (dummy) may become obsolete or less applicable.

The study shows that the AEB-induced OOP results in an increased risk of whiplash injuries in the follow-up rear-end collision. The increase of injury risk depends on the type of occupant model used in the simulation and has been done for only one collision severity case, one braking pulse and one vehicle. However, the initial results of this study indicate already that the whiplash assessment protocols for cars equipped with AEB systems should include the effect of AEB-induced OOP. Addressing the above problem would require, though, a robust method to identify the position of the occupant (including dynamic effects) at which he or she enters the in-crash phase.

The negative effect of AEB-induced OOP in the rear-end collision can be alleviated effectively by applying different occupant motion control measures deployed in the pre-crash phase. The main mechanical principle of the investigated system configurations is the reduction of the distance between the occupant and the backrest and headrest. The highest effectiveness in reducing the negative effect of AEB-induced OOP was obtained for the system with active headrest and motorized belt pretensioner.

Both investigated occupant models showed significant differences in predicting the pre-crash occupant motion resulting from AEB deployment, and thus also in the injury results in the follow-up rear-end collision. The severe OOP recorded with the BioRID-II model can be explained with the fact that the dummy is not validated for frontal loading, neither is it mechanically designed for use outside the in-plane rear loading and rebound phase. No mechanism in the BioRID-II can provide thoracic stiffness in flexion, thus resulting in an excessive (when compared to testing with volunteers in similar testing configuration [12]) forward motion of the upper torso under a braking loading.

It can be concluded that the BioRID-II and its model cannot represent the forward motion of the occupant during the pre-crash phase and cannot be used for these purposes. Further studies should include feasibility and effectiveness of using AHM to predict the forward OOP induced by AEBS and then swap the BioRID-II model at the moment of rear-end crash start ($T=0.0$ [s]). This approach ensures that in both pre- and in-crash phases the adopted ATDs are adequate and validated for the loading conditions of pre- and in-crash phases.

Further studies into this problem should increase the confidence in the conclusive statements of this paper by:

- broadening the scope of the investigation (different rear-end crash severity, braking pulse)
- sensitivity study into testing condition parameters: seat geometry, seat characteristic compliance, seating position of the occupant

In conclusion, given the significant injury risk typically accompanying rear impact collisions also at very low relative speeds [4] and the yet limited understanding of the potential for integrated safety to address this issue, this paper intends to initiate the interest in further research that can exploit new predictive technologies to reduce the harm caused by rear-end impact.

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